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Power Transmission Technology for the 1980-1990 Time Period

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POWER TRANSMISSION TECHNOLOGY FOR THE 1980-1990 TIME PERIOD

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It is a great pleasure for me to have this opportunity to present to you a subject that is very close to my heart - future transmission systems. Electrical demand in the U.S. is doubling every ten years. While the electric growth capacity characteristics are being questioned for the future, the best estimates are that this will continue at least through the 1990's.

Load tends to be concentrated in cities and historically generating plants were located in cities. Environmental considerations for fossil plants are tending to locate them away from cities and the trend is expected to continue. Reluctance to accept nuclear plants near larger cities results in locating these out of cities. Transmission will become increasingly important not only to bring energy from remote plants to the cities but to provide interconnections between areas for improved reliability in emergencies and to take advantage of area diversity in demands.

When we look at our crystal ball and try to find out how transmission systems will be designed in the year of 1990, we must try to answer several questions:

1) What is the next level of transmission voltage?

2) Is it going to be overhead or underground?

3) Is it going to be AC or DC?

4) What are the technological advances we can predict for transmission equipment?

5) How about the non-conventional ideas of power transmission such as microwaves and solar energy?

6) How do we plan for the transmission system in the year 1990?

1. Next Voltage Level

In 1889, the first alternating current transmission in the United States went into service at Oregon City. Power at 4000 volts was transmitted 13 miles to Portland, Oregon. During the next 24 years significant progress was made and by 1913 transmission voltages were up to 150 kV.

The evolution of transmission voltage continued increasing to 165 kV in 1922, 230 kV in 1923, 287 kV in 1935, 345 kV in 1953, 500 kV in 1965 and 765 kV in 1969. With the increasing demand for electric power, we are now led to the threshold of ultra-high voltage (UHV), voltages at 1000 kV and above.

In Pittsfield, Mass., the General Electric Company has been conducting a research project under the sponsorship of the Electric Research Council, and more recently, The Electric Power Research Institute. This is the Project UHV and its purpose is to find out what are the problems and how to solve these problems if we have to design transmission systems at voltages as high as 1500 kV. Perhaps you might be interested in some of the surprises in the insulation system design as we move from 345 kV to higher levels.

At 345 kV, lightning used to be the most important design criteria, i.e., if your insulation system can withstand the lightning voltage that it is supposed to, then it can withstand any other sources of overvoltage the system may impose upon it. Lightning is a very fast rising voltage wave, rising to its peak in a matter of a microsecond and decays in some tens of microseconds. When we move to 500 kV, we found that a much slower rising voltage caused by the operation of circuit breakers is a much more difficult duty. This is the so-called switching surges. These surges rise to the peak in a time period of several hundred microseconds. Switching surges have peculiar characteristics like shown in Figure 1. It does not always cause a breakdown to ground which is closest to the source of high voltage. Here instead of breakdown to the nearest ground which is 26 ft. away it chose to arc over to a trailer and trees which are 80 to 150 ft. away.

At 765 kV we find that may be switching surge is no longer the most severe duty. Instead, the contamination on insulators may prevent them from withstanding normal system voltages. If we can design systems to withstand that, then lighting and switching surges may be nothing to worry about.

We are finding other new problems at these ultra-high voltages. For example, in foggy weather UHV transmission lines may emit audible noise like fire crackers. If a truck is under a UHV line it may be charged up to a high enough voltage so that anyone who touches it may get a shock. All these problems require R & D to solve and we are working very hard on them. It is probably safe to say that 1100 or 1200 kV will be technically feasible very shortly and voltages as high as 1500 kV may prove to be feasible.

As we think about the next voltage level, though, we must face a rather important question. In our country, we really have two power systems. One consists of the voltage levels of 115, 230 and 500 kV and the other one - 168, 345, 765 kV. For every system voltage level, we must conduct R & D for system design and equipment development. This

Figure 1. Switching Surge Test on 1500 kV Transformer Bushing

costs money. For the next level, wouldn't it be wise if we have a single voltage level such as 1250 or 1300 instead of going merrily the same way as before: 1000 kV on top of 500, 1500 kV on top of 765? But this calls for some statesmanship or better yet, the elimination of some of the one-upmanship to do it.

2. Overhead or Underground

Now the second question: Is it going to be overhead or underground?

To put this in perspective, today there are about 250,000 miles of overhead transmission lines at 115 kV or higher in the United States but only about 1800 miles of underground cables at voltages of 115 to 345 kV. The pertinent reason for this difference is the relatively high cost of underground transmission.

In an overhead transmission system, insulation is obtained by porcelain or other insulators at supporting structures and sufficient clearance in air. Heat losses in the conductors are dissipated readily to the air.

Today's conventional high voltage cables consist of a conductor insulated with oil impregnated paper tapes and covered by a metallic ground sheath.

Where several feet of clearance provided insulation for an overhead system, insulating paper tapes with a total radial thickness of the order of an inch must provide equivalent insulation for an underground cable. At 500 kV for example, the cable insulation thickness is about 1.25" compared to 10 to 11 feet air clearance at supporting towers of an overhead system. Where overhead conductor losses are readily dissipated to air, in the underground system losses must be dissipated through the cable insulation and then through the earth, both relatively good heat insulators. To prevent deterioration of the organic insulation by temperature, an underground conductor must be operated at a considerably lower current than the equivalent conductor size in an overhead system.

In an underground AC system, there are additional losses in the insulation which must be dissipated and the charging current of the cable limits the length which can be used without compensation; an expensive addition with environmental impact.

To provide a reliable high voltage cable, careful control must be exercised in material selection, manufacturing processes and installation. Cable splicing must be performed in a clean, low humidity atmosphere.

Excavation and backfill processes for cable installation are costly particularly in areas with considerable rocks.

Underground installation in open country is not without environmental impact since right of ways in the width order of 50 to 100 feet must be cleared to permit installation and future maintenance.

Underground cables are in use today at 345 kV and recently completed tests at the EPRI Waltz Mill test facility have confirmed the availability of a 550 kV cable. Underground transmission is costly, ranging from 10 to 20 times the cost of overhead. The situation is much different than that for the lower voltage distribution system where undergrounding may be done at 1.5 to 2.0 times greater cost than for overhead.

Where it is possible to obtain overhead right of ways at reasonable cost or to develop utility corridors, overhead will always be less expensive than underground transmission. However, environmental conditions or prejudices which force generating plants out of cities and which ban overhead lines on scenic or historic areas will result in increasing use of underground transmission, despite higher costs.

Recognizing the need for lowering the cost of underground transmission and for providing for the higher capacity circuits that will be required in the 1990's, the Electric Power Research Institute has an active program for research and development in underground transmission. Since projected costs of new systems are not always realistic until research and development is complete, work is underway or planned for different types of systems which may serve the same circuit capacity requirements. This assures an ultimate selection of the most economic system for the required capacity.

I might mention here that some proposed systems appear to be economical for circuit capacities considerably higher than presently acceptable for system reliability but which are likely to be acceptable in the 1990's when unit generator capacity and system loads will have increased markedly.

Programs completed or actively in progress under the direction of the Electric Power Research Institute include:

1. The construction and operation of a test station by Westinghouse at Waltz Mills, Pa. for testing various underground transmission systems up to 1100 kV AC.

2. Increasing capacity of conventional cable circuits by forced cooling, including the use of refrigeration.

3. Development of synthetic paper and synthetic laminar cables for the purpose of decreasing insulation losses and thus increasing ratings at present voltage levels and making possible at least an 800 kV AC cable.

4. Development of compressed gas insulation systems. Several short sections of such a system have been commercially installed at 345 kV. They are a cylindrical aluminum conductor supported by insulating spacers in a larger aluminum sleeve having an outer corrosion protection coating. The space between the inner conductor and outer cylinder is filled with an insulating gas under pressure. SF_6 at a nominal 22 psig has been used.

   Three single phase assemblies constitute a three phase system. These systems have the advantage of materially reducing charging current for AC operation, are relatively simple in construction and have a minimum of accessory equipment. However, present size and installed cost are a disadvantage. Capacities of 1000 to 2500 MVA are readily obtainable and forced cooling would provide higher capacities. While systems have been designed to 345 kV, satisfactory operation is expected at voltage up to 1000 kV. Research continues on three phase systems, spacer insulation, gas mixtures and higher gas pressures.

5. Study of the breakdown mechanism in ex-

truded cross linked polyethylene cable. Extruded cables are simpler to manufacture. Such cables are on test at 138 kV at Waltz Mill. Whether their use can be extended to higher voltages will depend on a better understanding of the mechanism at failure in extruded materials.

6. Cable Joint Simplification. A very desirable project to reduce the time and conditions under which splices presently have to be made.

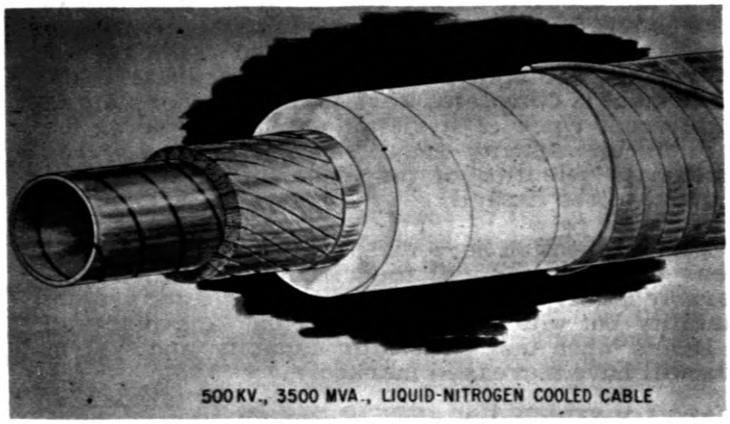

Figure 2. 500 kV, 3500 MVA, Liquid-Nitrogen Cooled Cable

7. Resistive Cryogenic Transmission System. A resistive cryogenic AC transmission system takes advantage of the substantial reduction in resistivities of metals such as copper or aluminum at very low temperatures and consequently reduces the ohmic losses in a transmission system. G.E. completed a project for Electric Research Council which resulted in the manufacture of a 500 kV cable design (Figure 2) using an aluminum conductor cooled by liquid nitrogen and insulated with Tyvek tapes. The prototype tested by Phelps Dodge Wire & Cable Co. withstood rated voltage but failed at 20% overvoltage. A three phase cable in an 18 inch pipe has been designed to carry 3500 megavolt-amperes at a system voltage of 500 kV. (Figure 3) An extension to this contract has been authorized by EPRI for the development of an improved insulation

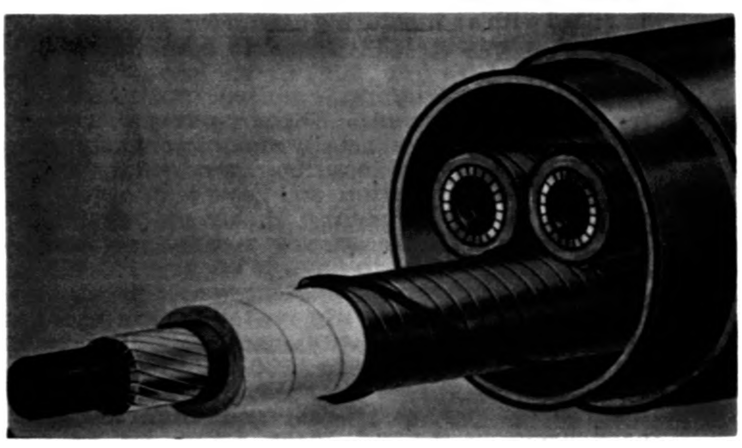

Figure 3. 3-Phase, 500 kV, 3500 MVA, Liquid-Nitrogen Cooled Cable

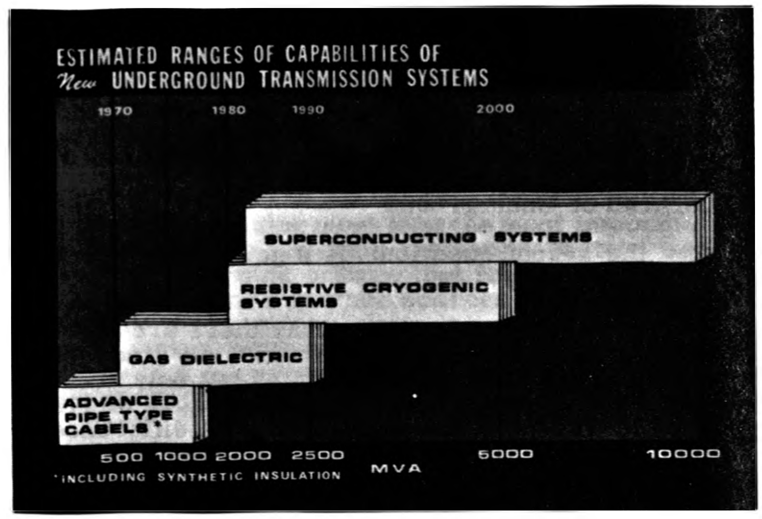

Figure 4

system and demonstration of its suitability and long term stability. The overall objective is to make available a commercial system by the 1980's in the 3000 to 4000 MVA range. Other research organizations are studying cryogenic insulation materials and the use of vacuum insulation systems.

8. Super Conducting Cable System. A super conducting cryogenic transmission system utilizes the properties of certain metals which have zero resistance below a certain low transition temperature. Research by the Linde Division of Union Carbide for the Electric Research Council has shown that niobium has sufficiently low AC losses to suggest its use for an AC transmission system. A further EPRI project assigned to the same company has the objective of demonstrating the feasibility of building an economic system for the transfer of power in the order of 1,000 to 10,000 MVA at voltages in the 138 to 345 kV level. This system envisions the use of niobium plated copper conductors supported on the dielectric spacers with liquid helium at about 4° K as both the electrical insulating and cooling medium. A thermal insulating system combining the use of high vacuum and super insulation is necessary. Refrigerating plants would be installed approximately every five miles. Pre-fabricated transmission sections of 40 to 60 feet are planned.

Improvements in very low temperature thermal insulation techniques and in the efficiency of high capacity cryogenic refrigerators would be very useful in reducing cryogenic system costs.

Different types of underground systems vary widely in power handling capacity. Estimated capacity ranges of several systems are shown in Figure 4. Costs of underground systems vary with the physical characteristics of the system, the capacity to be transferred, elevation changes, length of circuit and type of terrain. Comparisons should be made for a specific installation. An estimate of the cost range

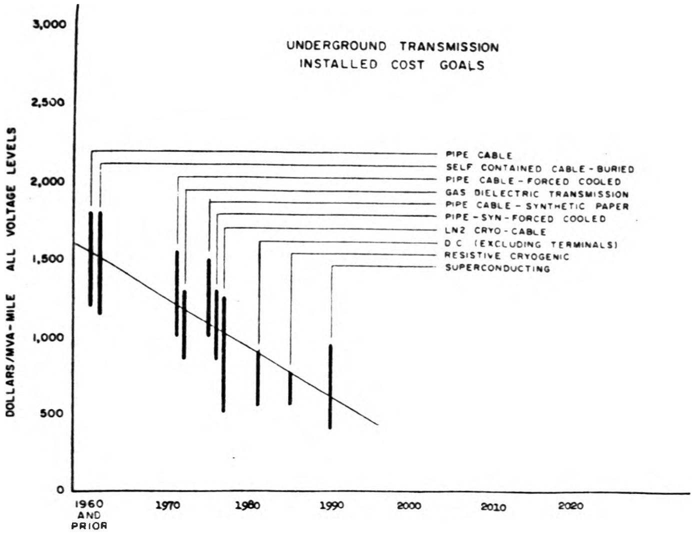

Figure 5

for various types of underground transmission systems is given by Figure 5. It should be emphasized that these are the best present estimates and involve some systems which have not yet been proved commercially feasible.

Other underground developments expected to be pursued include systems for mapping existing underground structures by an appropriate survey from the street surface and improved installation methods. The first would provide savings in planning a new underground system and the second would hopefully reduce to some extent the very costly procedure of excavating and backfilling for underground systems.

The June 1971 report of the R&D Goals Task Force to the Electric Research Council recommends research and development expenditures of $344,000,00 for AC underground transmission, $85,000,000 for AC overhead transmission and $116,000,000 for DC transmission through the year 2000.

The recommended expenditures for AC underground transmission should provide commercially feasible designs to transmit desired capacities as required in this period at the most economical cost. It is not to be expected the underground costs will be as low as overhead costs where overhead right of ways are feasible. Overhead systems will continue to be the major transmission mode for AC through this period unless the public decides that the benefits for putting electrical transmission underground far outweigh other social improvements which might be made with the savings involved in constructing overhead transmission.

3. AC or DC

The third question is: Is it going to be AC or DC?

It has been recognized for a long time that basically DC transmission lines cost less than AC for the same power to be transmitted. But AC has many advantages. It is easier to generate AC, its voltages can be stepped up or down at will; and you can tap into an AC line anytime and at any place that you wish. Thus, for many years, DC was only considered either for very long distance point-to-point transmission or some underwater crossings where the savings in cable cost are significant. Even though for these applications, special conversion equipment had to be developed.

The high voltage mercury arc rectifier developed by ASEA in Sweden represented one of the major advances in HVDC transmission. Underwater crossings first went in on the island of Gotland and subsequently we found more applications such as the cross channel link between England and France, lines to tie two different frequencies together in Japan, and finally the major DC line that runs 800 miles from Dalles in Oregon to Los Angeles.

As experience was mounting on the operation of HVDC systems, we also find many other advantages of DC. They can help to stabilize AC systems during transient disturbances, they can help to limit the short circuit current in the power systems, they can tie asynchronous systems together and they can be controlled in terms of the amount of power to be transmitted in a predetermined way. Interest in DC started to mount in the '60's.

At about the same time that decision on the West Coast Intertie was made, we in the General Electric Company had a major decision to make. Should we extend our mercury arc technology for industrial applications to HVDC transmission or should we leapfrog the state of art with a new technology. We were impressed with how rapidly semi-conductors were displacing mercury arc rectifiers in industrial applications. Even though, the power semiconductors were not large enough in voltage and power ratings to make them attractive for HVDC application, we had faith that technology will continue to advance to the point that it will displace mercury arc rectifiers in HVDC applications just like they did in industrial applications. Therefore in 1964, we started a program to develop solid state HVDC conversion system, I might add that amid pessimism in the entire industry, domestic and abroad, of the future of silicon controlled rectifiers for HVDC. Eight years later, I am pleased to report that the entire industry is going our way. SCR's now are the facts of life for DC transmission.

Let me go through with you the progress we have made. We developed a 40 MW back-to-back system (Figure 6) and ran it in our laboratory for some time. Then we built and tested a 200 kV valve in 1967. (Figure 7) This valve represented a single unit as high in power rating as we anticipate needing and it is still the largest valve that has ever been tested.

Figure 6. 40 mW back-to-back HVDC Conversion System

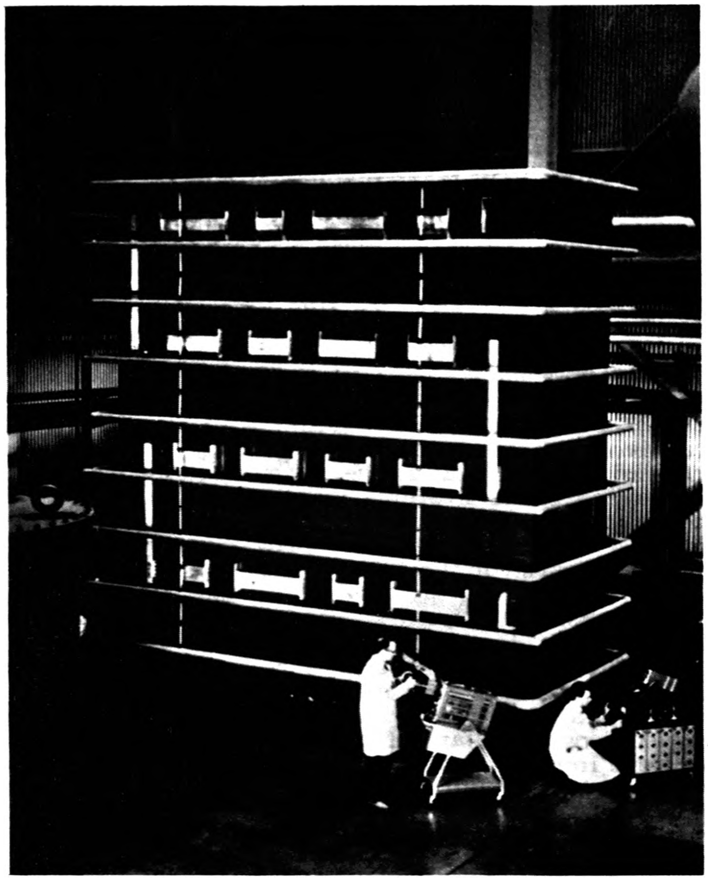

Figure 7. HVDC Conversion System 200 kV Valve

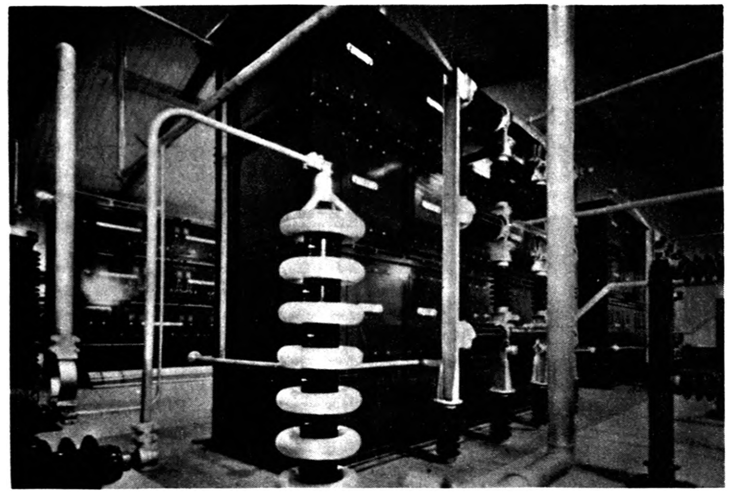

Figure 8. Valve Hall - 320 mW HVDC System at Eel River, Canada

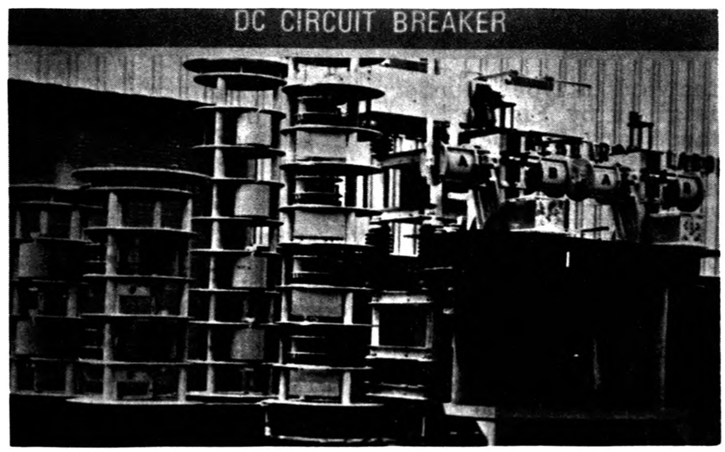

Figure 9. 80 kV - DC Breaker

in 1967. (Figure 7) This valve represented a single unit as high in power rating as we anticipate needing and it is still the largest valve that has ever been tested.

We were very pleased to receive an order from the New Brunswick Electric Power Commission in 1969 for a 320 MW asynchronous tie between the power system of Quebec and New Brunswick. In 1972 we energized the World's first semiconductor HVDC system at Eel River, Canada, (Figure 8) and for the first six months, it had an availability of 98.5%, an unheard of record in HVDC history. Here we were benefited from the experience we had in applying the quantitative reliability techniques developed for space and miliary industries.

In working on HVDC systems, we recognized the fact that if we can tap a DC line the usefulness of DC will be greatly enhanced. To do this, we need HVDC circuit breakers. But there was no HVDC breaker available anywhere. The reason is, of course, that this is a very difficult job technically, so we decided to tackle the problem. A few years ago, we developed an 80 kV DC circuit breaker to demonstrate a principle. (Figure 9) Since then, we found a very interesting application for this principle. M.I.T. was involved in thermonuclear fusion research under the sponsorship of AEC. They needed a very fast HVDC switching device to divert current out of a superconducting coil to induce a voltage to pinch the plasma to temperature in the order of hundreds of million degree centigrade for fusion reaction. We produced such a device for them utilizing the same principle. We are now ready to build HVDC circuit breakers at any practical rating that our power systems may require.

Looking at the future of DC then, we can see tapped lines. We can see much lower conversion costs; we can see compact DC conversion terminals which will make the DC substation much smaller; we can see lower cost DC cables which make it economical to transmit power from a remote generation site to a metropolitan city via the underground route, and we can see DC to be a key factor in trying many power pools together in our country. But for laymen, the question is often asked: Will DC replace AC? I think the answer is no. Our transmission lines, in general, are not that long, 200 miles on the average. We already have a strong AC system. Thus, DC will always be, in my opinion, a complement to our AC system but I believe its usefulness will be ever increasing.

4. Technological Advances

The fourth question is a natural one: Will the equipment needed be available? What are the technological advances that we can expect? To answer this

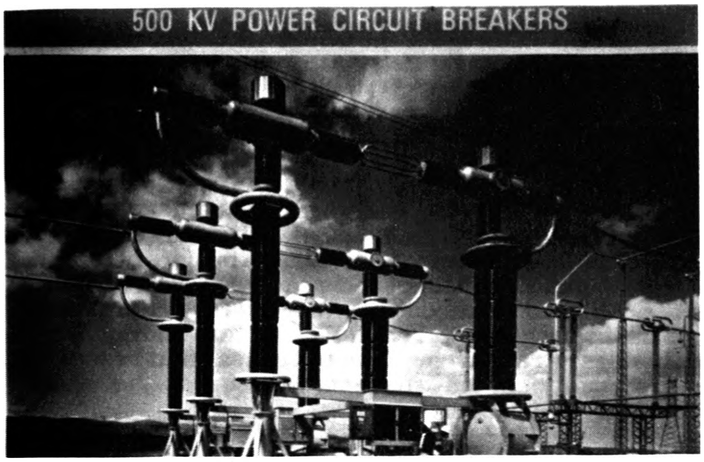

Figure 10. 500 kV Air Blast Circuit Breaker

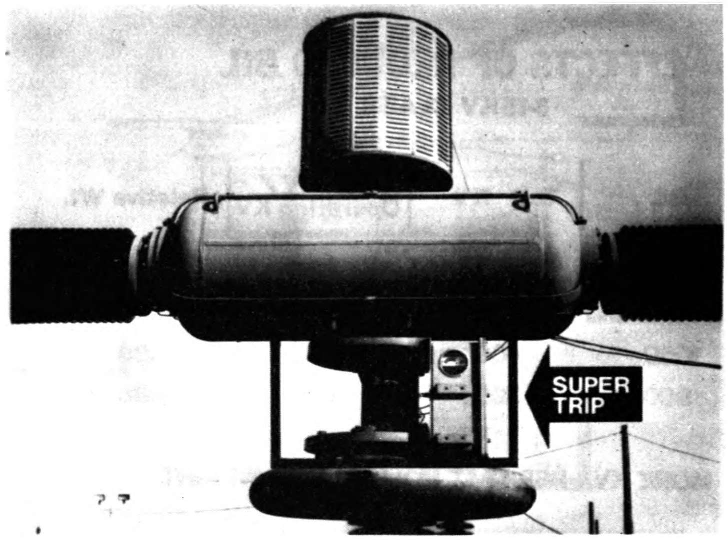

Figure 11. "SuperTrip" - A Device for converting a standard 2-cycle, 550 kV Breaker to give 1 cycle performance

question, we must first of all recognize the fact that our transmission system has grown in an evolutionary way. So has the equipment for that system. Certainly, once in a while, some revolutionary changes take place, like nuclear energy, like gas turbines, like solid state HVDC. But for the next twenty years, it is probably safe to say that evolutionary growth will take care of most of our needs. Let me mention a few examples:

The evolution of Circuit Breakers has been most interesting in that they have not only had to keep pace with the increasing voltages and capacities of transmission systems but, with the growing demand for more system stability, have become more sophisticated.

Additional stability margins can be achieved by using faster breakers and independent pole switching of the circuit breaker. In the latter approach, the closing and tripping control for each breaker pole is independent of the other poles. With this arrangement, a single phase, line-to-ground fault can be opened and reclosed while the unaffected poles remain closed thus reducing system disturbances. Since experience has shown that breaker failures usually involve only one pole of a breaker, independent pole tripping does provide decided advantages.

It is well known that from a system stability standpoint it is desirable to get rid of short circuits as promptly as possible. About 40 years ago the industry began to demand higher speed breakers than were available. Since that time breaker interrupting ratings have been progressively reduced from 20 cycles to 12 cycles in 1930, to 8 cycles in 1933, to 5 cycles in 1938, to 3 cycles in 1944 and to 2 cycles in 1961. We have now taken another step in the evolution of breaker interrupting time. While our air-blast interrupter is available at 2 cycles for any rating of transmission voltage breaker, we have developed, under a contract for BPA, a means of converting the standard 550 kV breaker (Figure 10) to give one cycle performance. The device that makes this possible is termed a "Super-trip" because of its ultra-high speed and the fact that it is superimposed on a standard breaker. (Figure 11) The converter will be package mounted just below the interrupter tank.

Let us review just for a few minutes the advances which have been made in protecting our power systems against lightning and overvoltages. In 1890, the first commercial lightning arrester was introduced. In 1930, thyrite was invented. This was a great step in protection against lightning. However, it was not until 1954 when we were able to extend the application to protection against other types of overvoltages with the introduction of magne valve arresters. Since that time, there has been a steady improvement in the protection level, in the energy they can dissipate and in the overvoltage handling capability.

The advances in arresters had a tremendous influence on the size, weight and dimension of power transformers. Let's look for a moment at a cutaway of a transformer. (Figure 12) The area which we refer to as the core window, for typical high voltage power transformers, may consist of 90% insulation and 10% copper. If one can attain an improvement of 10% in

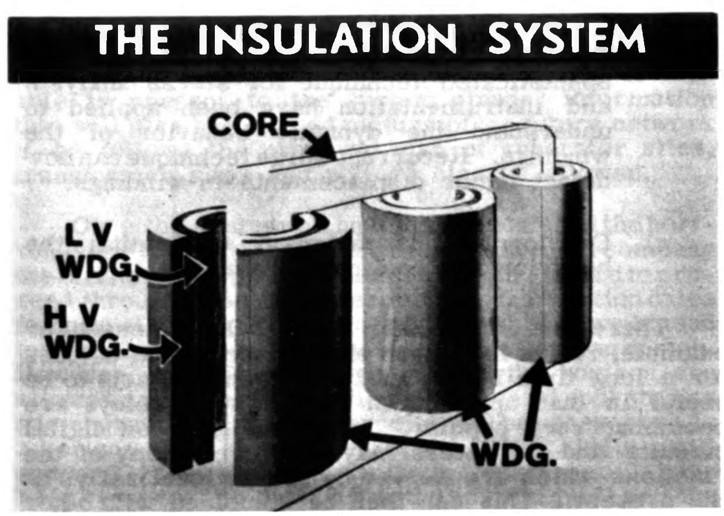

Figure 12. Cutaway view of Transformer

EFFECTS OF REDUCED BIL

345KV CLASS

BIL	Test KV	Test KV / Operating KV	Relative Wt.
1300	575	2.75	1.00
1175	520	2.50	.94
1050	460	2.20	.90
900	395	1.90	.86

MORE KVA PER UNIT VOLUME AND WEIGHT

Figure 13.

insulation effectiveness, copper space would increase to 19%. This suggests that a much higher rating can be assigned for the same size. Figure 13 shows the effect of reduced BIL alone on the weight of typical 345 kV transformers.

In the last 20 years, the power rating of transformers has increased by a factor of 10. Even with the improvement in weight per kVA, we are still facing a shipping problem. Imagine how bad the problem would be if we had not done the R&D on insulation systems and arresters.

Today, one of the most important considerations to power transformers is reliability. Let us take a quick glance at the R&D work to improve the reliability of transformers.

a) Great advances have been made in corona detections. Testing requirements are becoming more severe as we learn more about coronas and partial discharges.

b) On short circuit withstand capability, the most sophisticated technique for stress analysis and instrumentation have been applied to understand the dynamic behavior of the windings. Recurrent surge technique can now detect minor displacements in windings.

c) Development is underway to monitor the behavior on a continuous basis.

There are many other changes like these. For example, relays have been electromechanical devices for a long time but recently electronics starts to be useful in that application. Solid state relays are becoming very popular. As time goes on digital circuits and computers may take over many of the functions which are served by conventional relays at the present. This can then be combined with other functions that can be served by digital computers such as overall system control and substation automation. But these are the natural process of evolution. Suffice to say that technology will provide us with the equipment need for future transmission systems.

5. Unconventional Transmission

Guided microwave transmission has been suggested. In this system, the power plant generator output must be converted into radio frequency energy for transmission through a closed wave guide system and reconverted into 60 hertz AC power at the utilization terminal. Much research and development are required to determine the feasibility and economics of this transmission mode for large amounts of power. The wave guide is large and requires close aligning tolerances which may not be practical for underground systems in congested areas. Converters and couplers require basic research. It would appear that research on previously noted projects appear to be more productive at present.

The use of solar energy has been suggested. In this scheme light cells would be placed in orbit in space to absorb the sun's energy. Transmission would be by microwave from the orbiting solar energy converter to very large receiving areas in deserts. Conversion to DC would occur in these areas with DC transmission to points of utilization. Much research is needed for this scheme. There is the environmental question of dedicating to this purpose large land areas for the receiver station. There are hazards to air carriers in the vicinity of the micro-wave transmission. The tremendous expenditures required for research and prototypes, the environmental and hazard problems do not appear to justify pursuing this transmission mode while earth based fuel supplies exist for many years in the future.

Consideration has also been given to transmit energy in the form of hydrogen through pipe lines to generating plants near load centers where it would permit "clean" burning in city areas. This appears more prudent than other unconventional power transfer schemes but economic evaluation has not been finalized.

6. Transmission Expansion Planning

It should now be obvious that planning the transmission systems for the 1990's is a most difficult task because:

1) Equipment decisions have long term effects requiring a 15 to 25 year study period.

2) There are several alternate means of generating electric power, for example by nuclear, fossil or falling-water fuels and in large, medium or small size plants.

3) There are several alternate means of transmitting electric power, for example by alternating or direct current, overhead or underground, and at a wide range of voltages.

4) Uncertainty exists concerning the study parameters such as future fuel costs, interest rates on money, equipment forced outage rates and new technologies.

To help the planner formulate and evaluate the many and lengthy expansion alternates, a unique set of planning and simulation methods have evolved. These methods are implemented by digital computer programs and are directed by engineers trained especially for generation and transmission system planning.

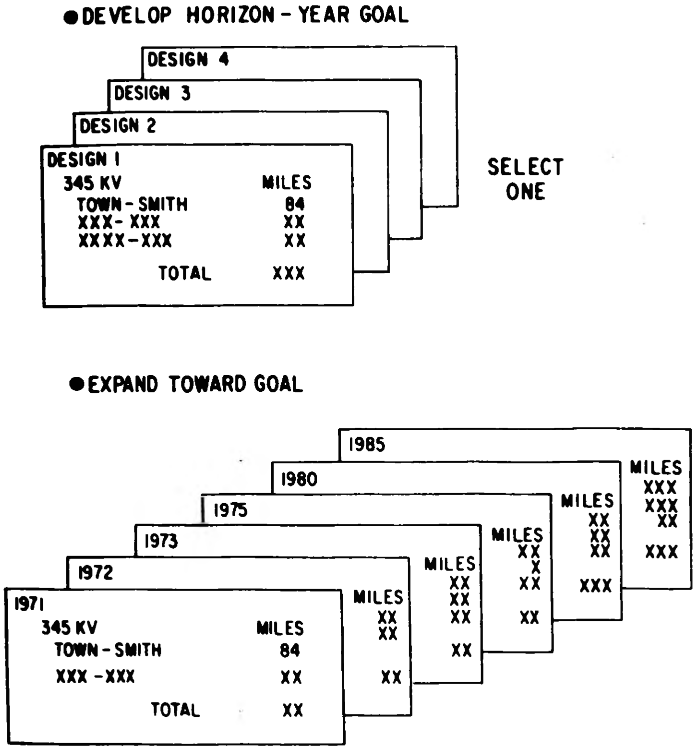

Figure 14. Two step approach to long-range transmission expansion planning

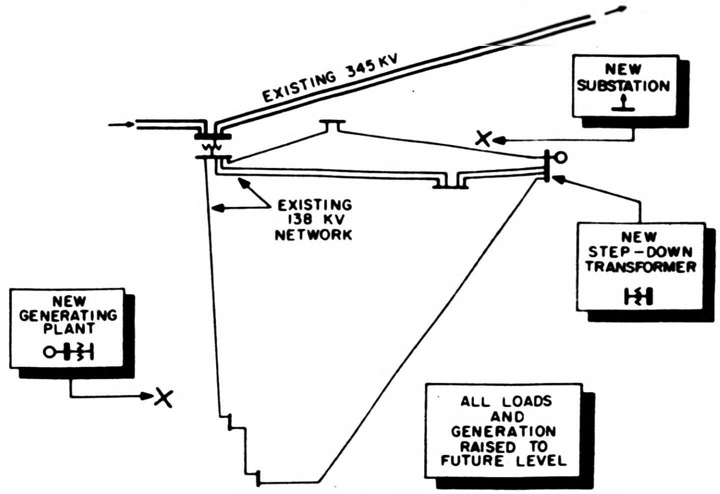

Figure 15. Initial network with future generation and load sites

Briefly, we start out with the assumption of loads for a horizon year and the permissible generation sites. For that the long term generation expansion planning is then computed using probability methods. In this program, the reliability of system reserve is evaluated. The transmission planning program lays out a sequence of transmission system additions that will be adequate from the viewpoint of system performance while achieving minimal expenditures. To achieve this objective transmission planning is done is two steps: (Figure 14)

1) A thorough study is made of the final year of the study, the horizon year, to determine the most desirable transmission system to have in place at the end of the study.

2) The original system is then expanded on a year-by-year basis adding transmission as required but at all times making sure that the additions specified are consistent with the horizon year plans.

The input data required by the Transmission Estimation Program is illustrated in Figure 15. Horizon-year designs are based on the following assumptions:

1) The existing network will be used as a starting point.

2) The location and magnitude of all future loads and generation are known.

3) The permissible voltage levels are specified.

The results from the Transmission Estimation Program include:

1) Summary of all input cases.

2) Circuit additions for each voltage class planned including the terminal points, the length in miles and whether this circuit was formed by looping an existing circuit into a bus, whether it was the second circuit on an existing tower line, or whether it represents a completely new construction.

3) The cause of the circuit addition, i.e., a generation-load schedule or a line outage test.

4) The total miles of circuits for each voltage class planned.

5) Power flow estimated for all generation-load cases and line outages with the circuit additions in place.

6) A list of possible alternate circuit additions, ranked in order of their estimated ability to improve the network.

The Transmission Estimation Program is thus able to present to the system planner information that will give him a good picture of his future network if he follows the proposed plan of generator sites, transformer sites and voltage classes allowed.

Once the system planner has determined the horizon-year design that appears best suited to his company, the Transmission Estimation Program is used to proceed through time and determine the installation dates for new circuits. The network additions are now biased toward those circuits appearing in the horizon design. However, circuits not appearing in the horizon are allowed as needed. Experience in several pool studies has shown that different circuits will be necessary. Is a horizon study that important if different circuits will appear? Plans developed without a horizon guide have been compared to those using the horizon guide and the plans biased by the horizon design have always proven more economic.